Nonlinear Effect of Resonant Magnetic Perturbations in Edge Collapse Simulations

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Overview

- Introduction
- Tearing parity fluctuation generation mechanism in edge collapse simulations
- Model and Simulations
- Effects of Resonant magnetic perturbations on the collapse,
  - Fluctuation evolution
  - Stochastization
  - Nonlinear energy transfer mediated by RMPs
- Conclusion and discussion

Introduction

- Edge Localized Modes (ELMs) is thought to be triggered by MHD peeling-ballooning instability.
- MHD filaments may carry out heat to SOL without reconnections. (Wilson and Cowley, 2004)

  Transport by the filaments may not fully account for the ELM driven transport. (Kirk et al., 2014)

- On the other hand, (Rhee et al., 2015) have proposed

  a nonlinear generation mechanism of tearing-parity fluctuations in ballooning driven simulations, implying a stochastic transport may take place.

- The nonlinear dynamics of ELMs is not fully understood.

Resonant Magnetic Perturbation

- Resonant magnetic perturbations (RMPs) are widely studied for ELM suppression and mitigation.
- The feasibility of ELM control by RMP is confirmed across several devices.
- Enhancement of turbulence has been observed when ELM is suppressed with RMPs(Lee et al., 2016).
- To address the nonlinear effect of RMPs on ELM crash consistently, we require flux driven ELM simulation of MHD, at least.

We study RMP effects on nonlinear evolution of fluctuations as extension of Rhee et al. (2015) in strongly ballooning driven pressure collapse with RMPs,

- This may provide insight into nonlinear RMP effects.

Model

Based on Hazeltine and Meiss (1992) with plasma response to vacuum field, $\delta B_{\text{RMP}} = \hat{\boldsymbol{b}}_0 \times \boldsymbol{\nabla}\psi^{\text{RMP}}$.

$$\begin{aligned}
\text{Vorticity} \quad &: \quad \frac{1}{v_A^2}\left(\frac{\partial U}{\partial t} + [\phi, U]\right) = -\frac{B_0^2}{\bar{B}^2}\nabla_{\parallel} J + \hat{\boldsymbol{b}}_0 \cdot \boldsymbol{\kappa}_0 \times \boldsymbol{\nabla}_{\perp} p \\
\text{Ohm's law} \quad &: \quad \frac{\partial \psi}{\partial t} + \frac{1}{B_0}\nabla_{\parallel}\phi = \eta J - \eta_H \nabla_{\perp}^2 J \\
\text{Pressure} \quad &: \quad \frac{\partial p}{\partial t} + [\phi, p] = f_K D_{RR} \frac{\partial^2 P_0}{\partial r^2}
\end{aligned}$$

where $\eta = 1/S = 10^{-9}$, $\eta_H = 10^{-12}$, and Rechester-Rosenbluth D_{RR}

$$U = \nabla_{\perp}^2 (\phi + p) \, , \quad J = \nabla_{\perp}^2 \psi + J_0 \, ,$$

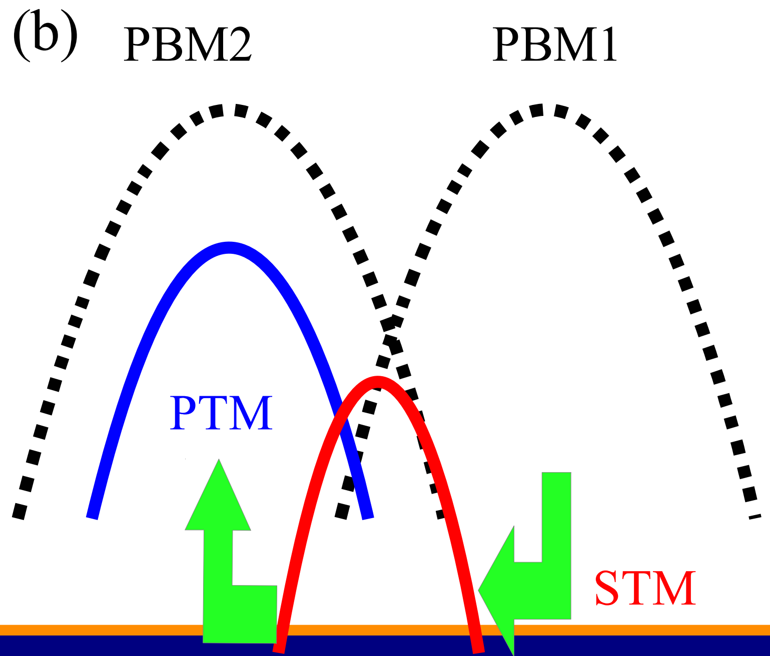
$$\nabla_{\parallel} \equiv \hat{\boldsymbol{b}}_0 \cdot \boldsymbol{\nabla} - \left[\psi^{\text{tot}}, \ \right] \, , \quad \psi^{\text{tot}} = \psi + \psi^{\text{RMP}}$$

and $\quad \psi^{\text{tot}} = \psi^{\text{RMP}} \quad$ at B.C.

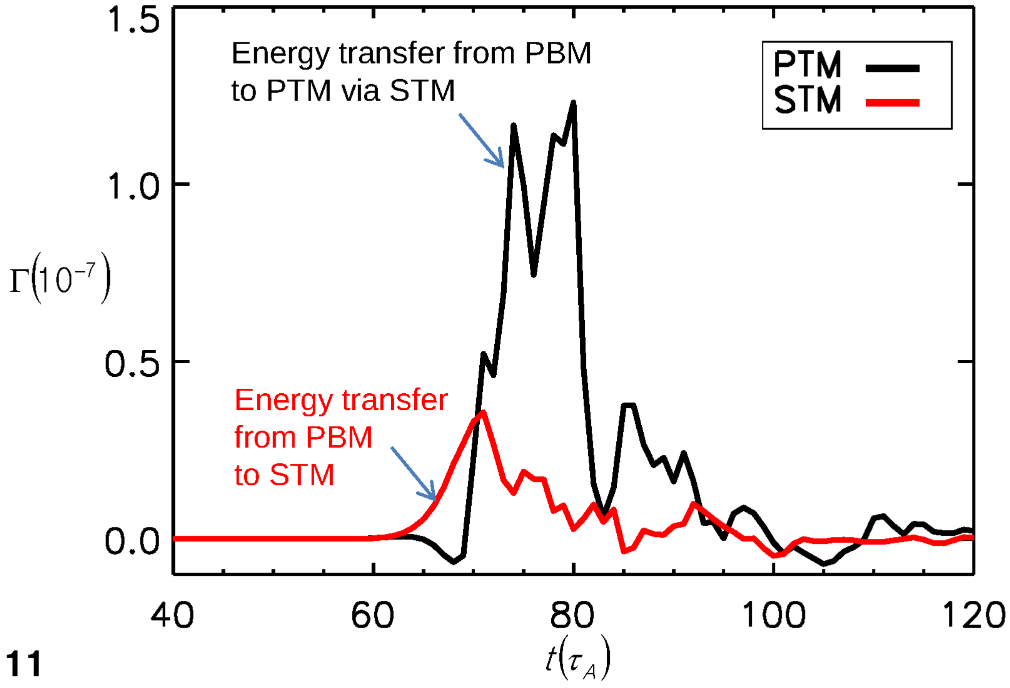
Stochastization mechanism by nonlinear BM interactions

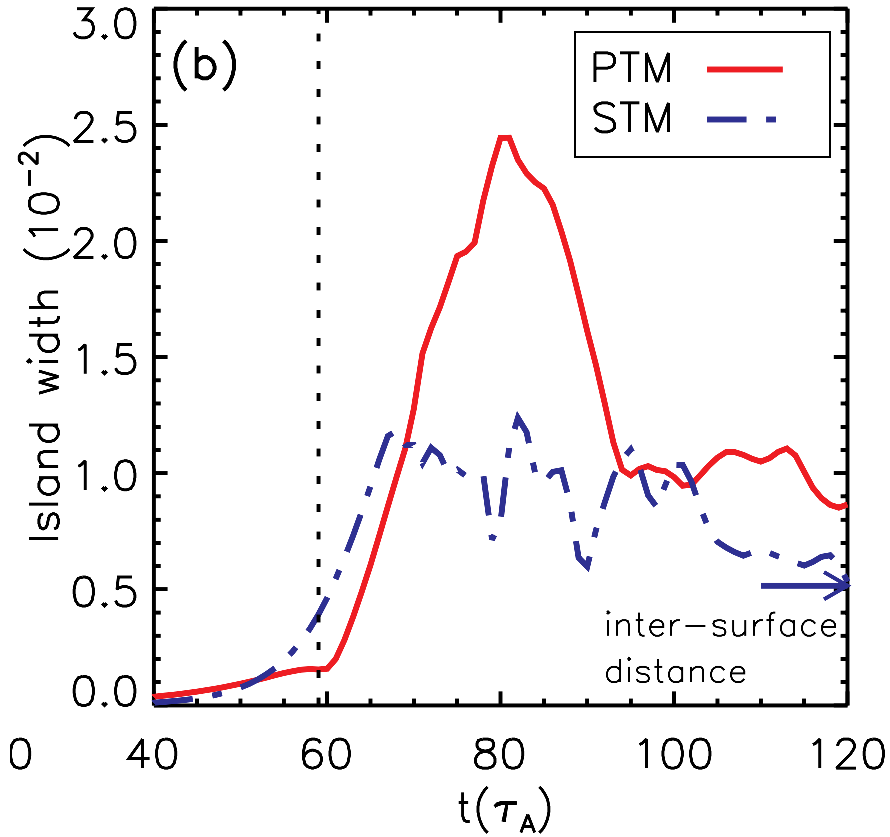
Rhee et al. (2015) proposes that field-line stochastization can happen by the mechanism

- Unstable n_0 primary ballooning modes (PBM) generate $2n_0$ secondary tearing-parity perturbations (STM) in-between the surfaces of their poloidal components.
- STM interacts back with PBM , generating tearing-parity n_0 perturbations (PTM).



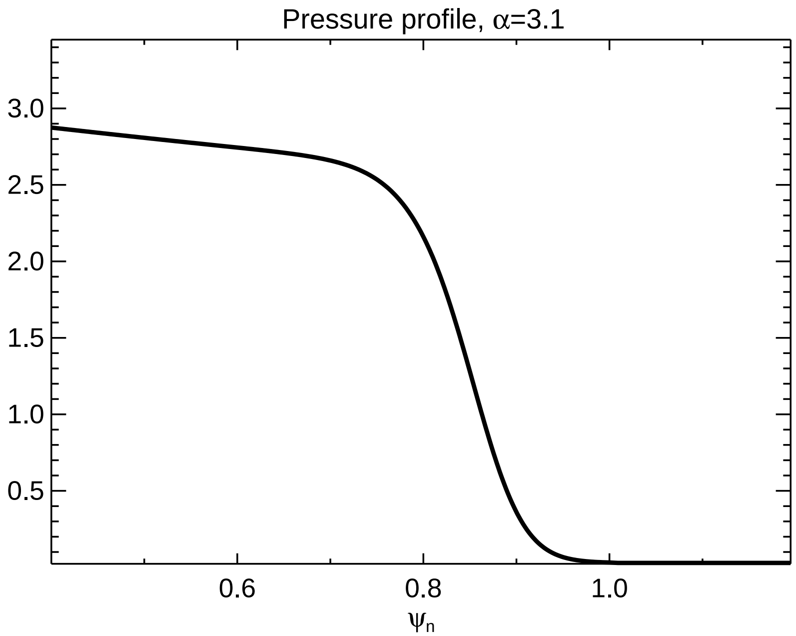
- STM is generated by the coherent interaction between BMs
  $\Longrightarrow$ STM growth rate $\gamma_2^+ = 2\gamma_0^-$ is twice of PBM growth rate (γ_0^-)
- PTM grows rapidly after STM island width reaches the inter-surface distance.





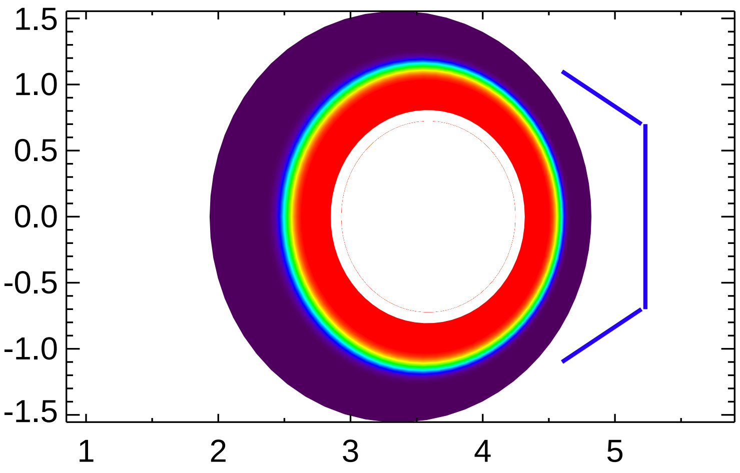
On the simulations

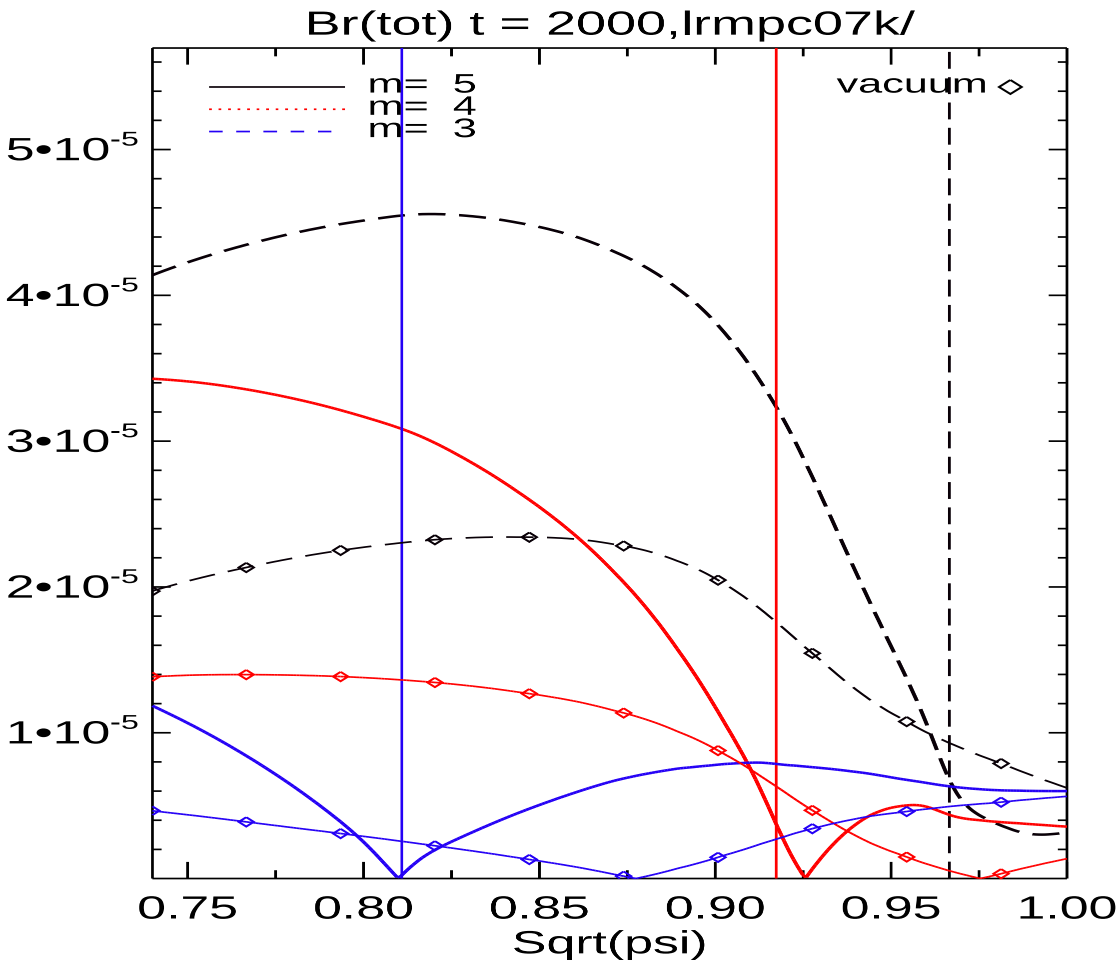
- In the BOUT++ framework [Dudson et al. 2011]
- $(n_x, n_y, n_z) = (516, 64, 128)$ in the half torus.
- The toroidal mode number $\boldsymbol{n} = 2, 4, \cdots, 60$.
- Maximum linear growth rates at $\boldsymbol{n} \simeq 20$, where $\alpha = 3.86 > \alpha_c = 2.8$ with $s = 4.36$.
- an initial Gaussian spectrum with the peak at $n = 20$.



- No sources/sinks
- No zonal flow($n = 0$ potential) : Jhang et al. (2016) on Zonal Flow
- No SOL/divertor physics and no X-points
- $S = 10^9$ but $J_{\|}$ smoothing and η_H
- $\nu_{\|} = \chi_{\|} = 10^{-2} \sim 10^{-3}$.

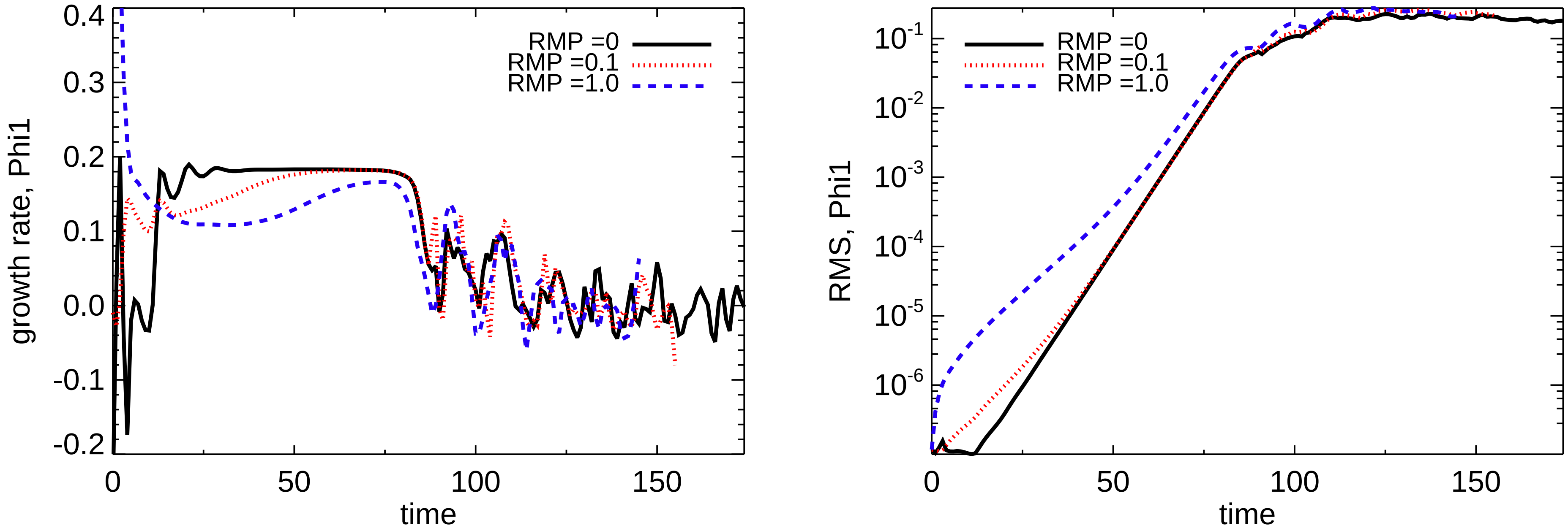
- We calculated a plasma responses ψ^{tot} to vacuum $n = 2$ magnetic perturbation from a set of 3×4 coils in the $\mathrm{BOUT++}$.
- Apply the plasma responses ψ^{RMP} for $n = 2$ as constants in time.
- The toroidal components $n = 2$ and 4 do not evolve in time.





Total fluctuations increases with RMPs

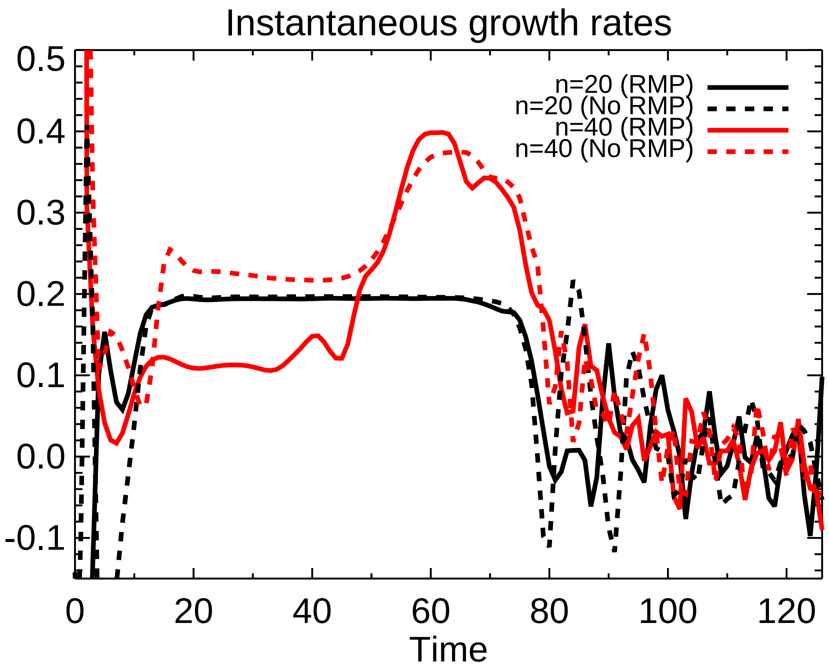
- Here, $|\phi|^2_{\rm rms}$ is shown for different RMP strengths.
- The simulations go through pre-collapse (t<80) and collapse (t>80) phases.

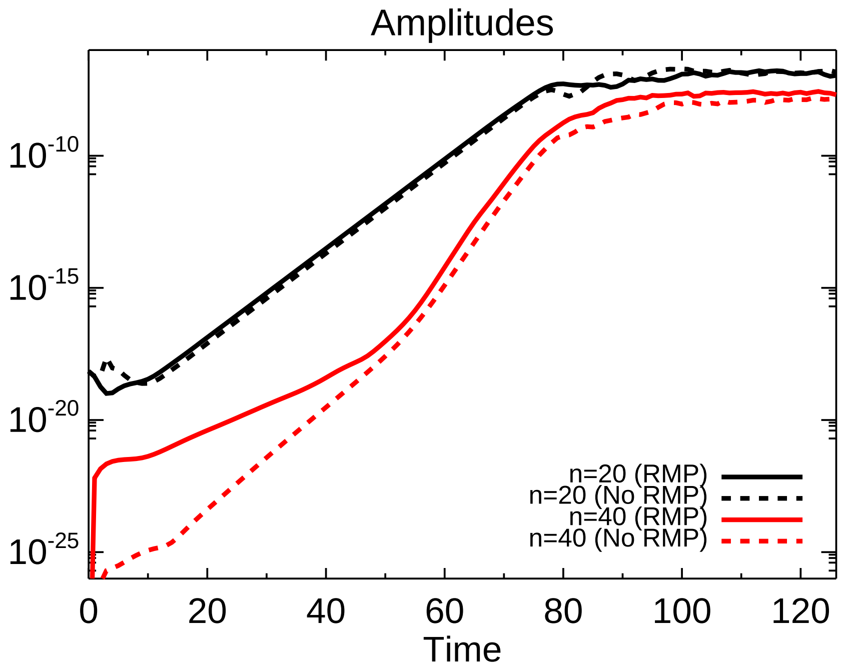


RMPs increase the fluctuation level in the whole simulation period.

The most unstable modes not affected by RMPs

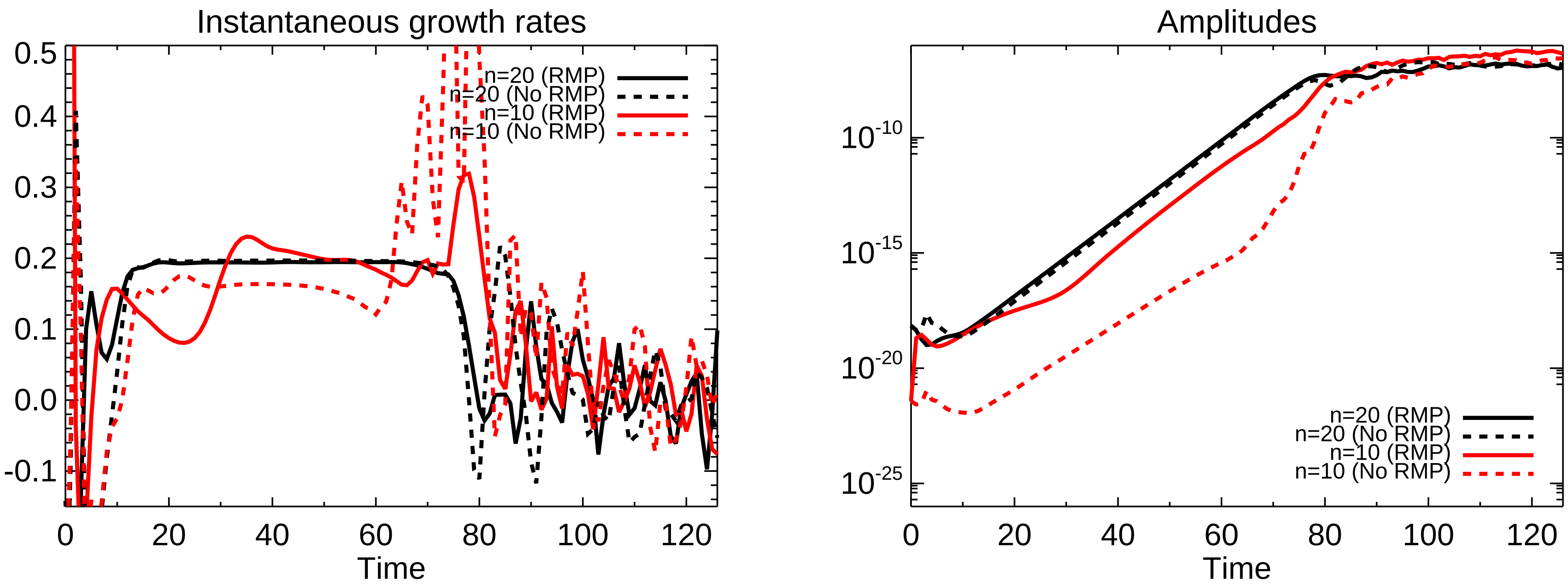
- Local curvature change due to RMPs (Bird and Hegna, 2014; Mou and Jhang, 2018) is missing, here.





- For higher n (i.e., $n = 40$), the early pre-collapse phase (t<60) shows enhanced fluctuations as in the previous slide.
- In the later pre-collapse phase, $50 < t < 80$, strong coherent interaction (Rhee et al., 2015) is observed, $\gamma \simeq 2\gamma_{\text{lin}}$.

Enhanced fluctuation at low toroidal number n

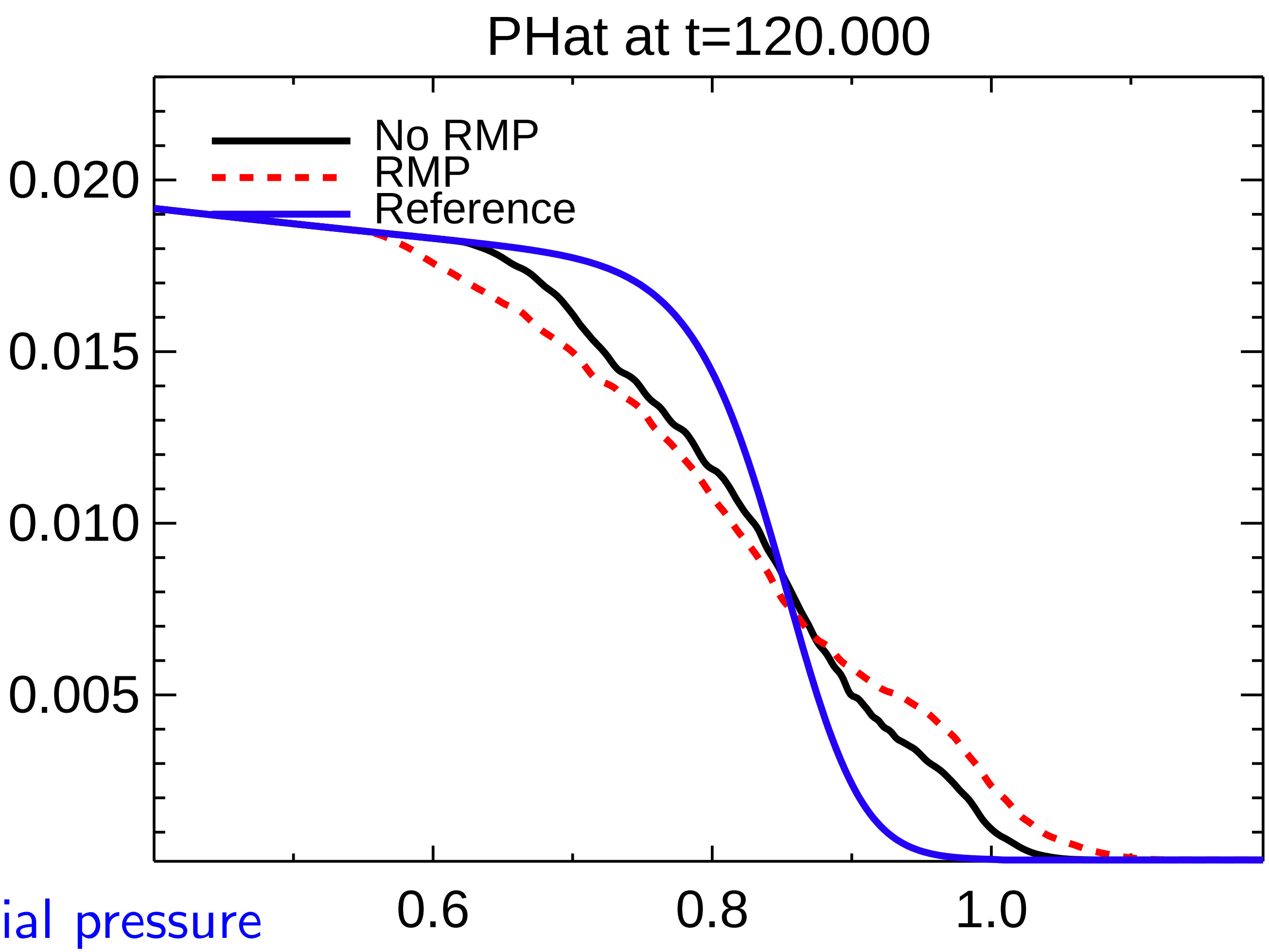


- For lower n $(\mathrm{i.e.}, n = 10)$, more enhanced fluctuation level with RMPs is observed throughout the simulations.

A hint of nonlinearly distinct evolution with overall enhancement of the fluctuations with RMPs

Fast pressure collapse

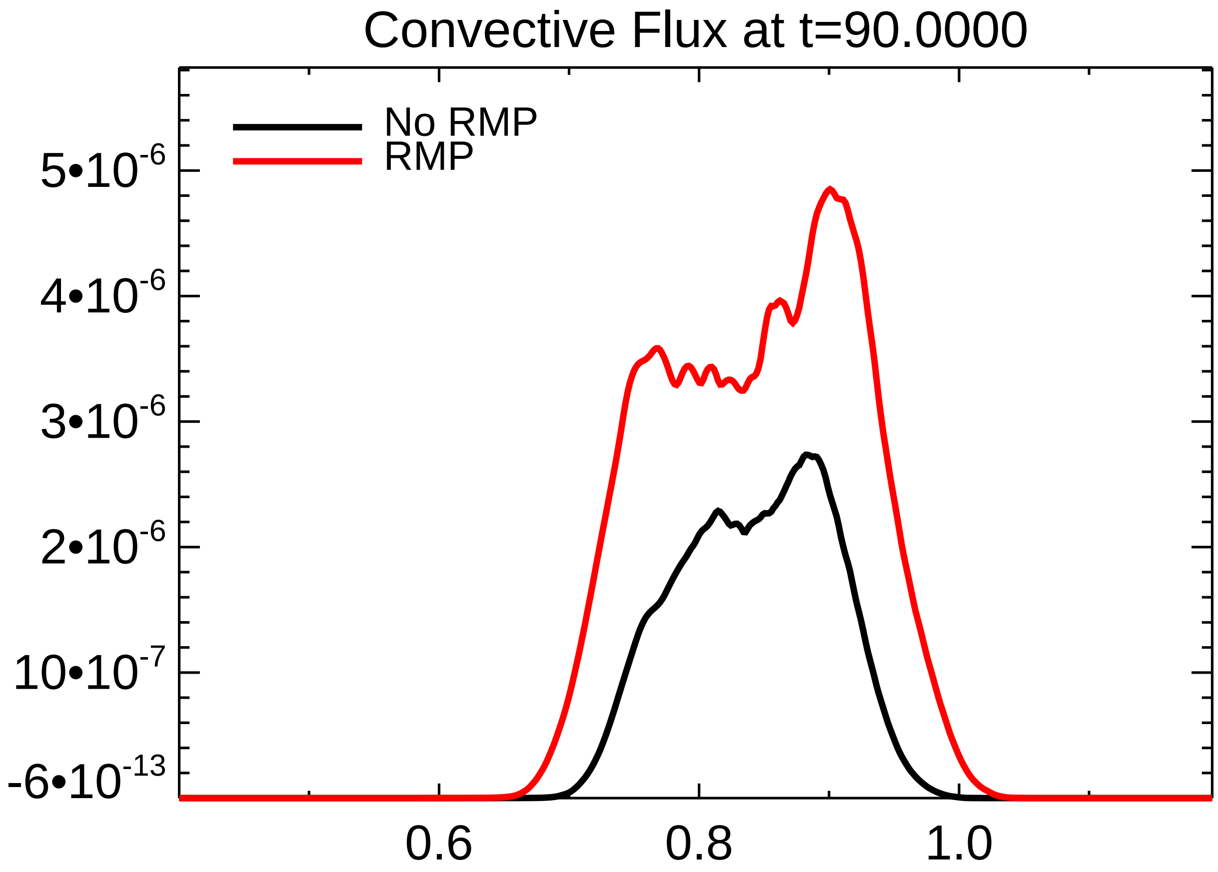
Before going into further analysis, let's see what's the impact of RMP enhanced fluctuations? In the collapse phases,



Reference : initial pressure

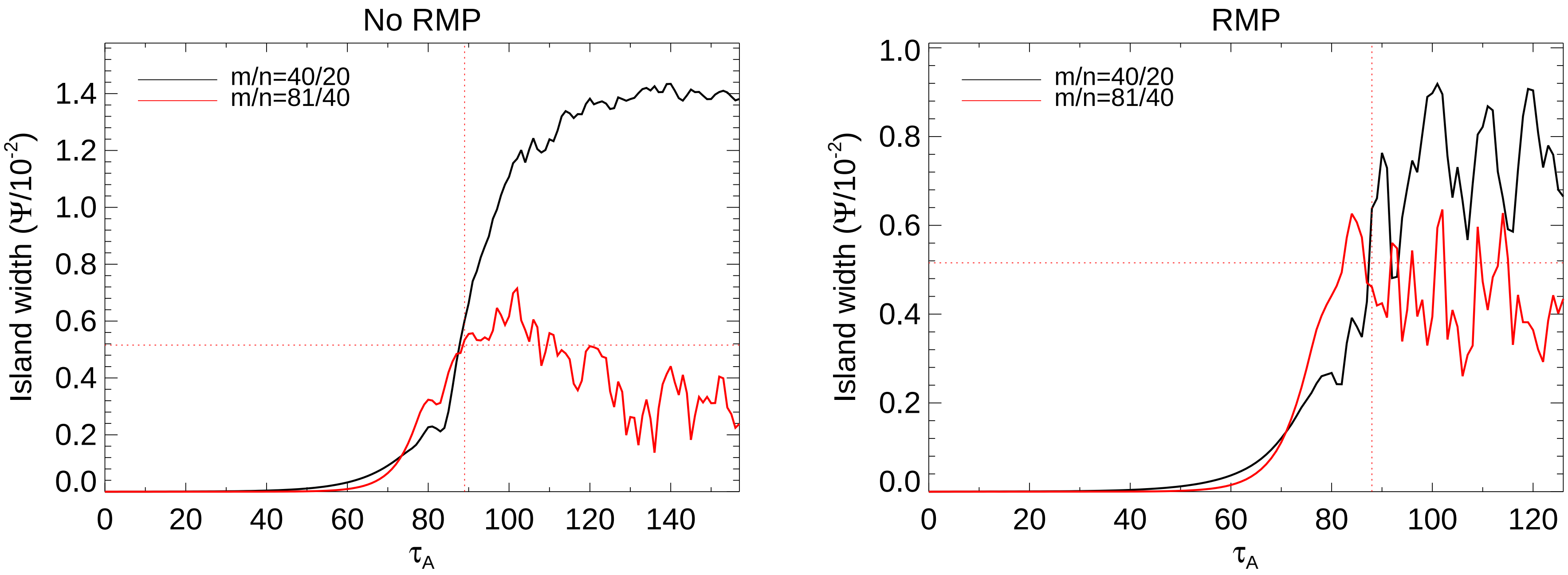
RMPs enhances the convective transport

- Larger fluctuations with RMPs leads to larger convective energy flux.



RMPs inhibit primary tearing modes? Yes, But...

- The primary tearing $n = 20$ increases abruptly at around the island overlapping, even though it is not well-timed as in the single-n simulations, due to the multiplicity of the rational surfaces.
  $\Longrightarrow$ In general, the multiple-n simulations follow the same mechanism but complicatedly.

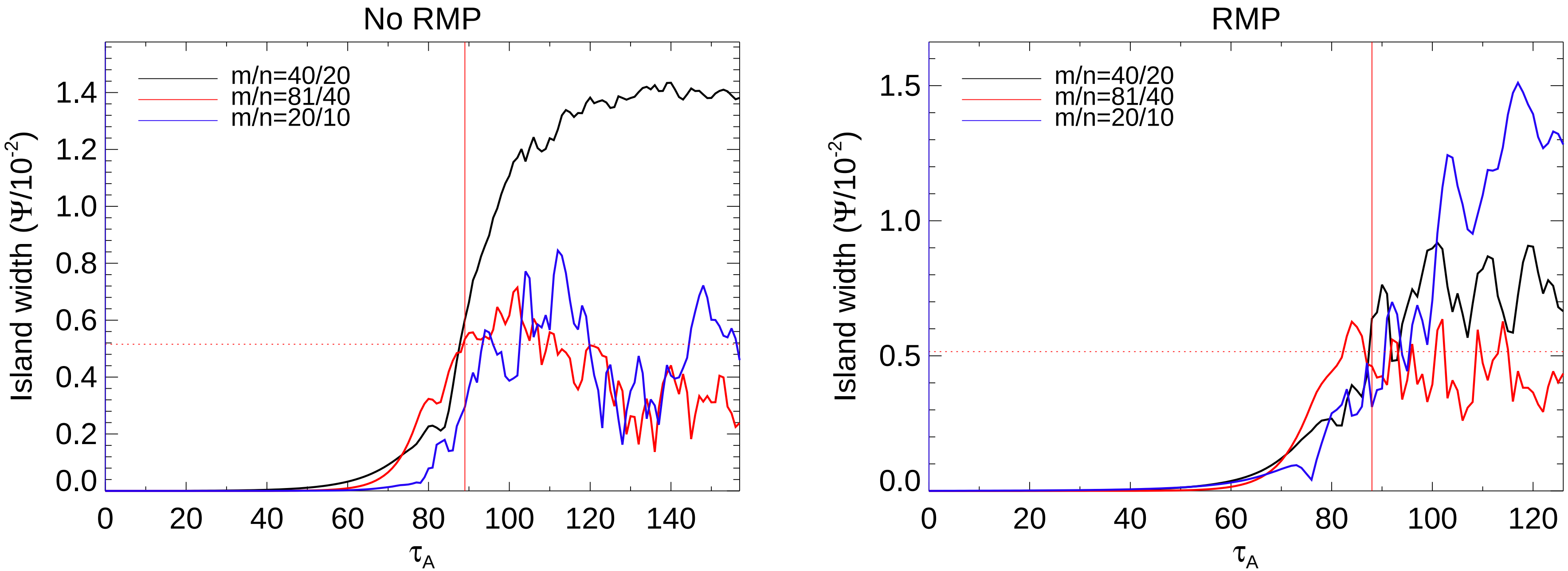


- Mainly, the primary tearing-parity fluctuations are relatively suppressed.

Why is the $n = 20$ tearing parity fluctuation suppressed with RMP?

With RMPs, a lower toroidal number becomes dominant.

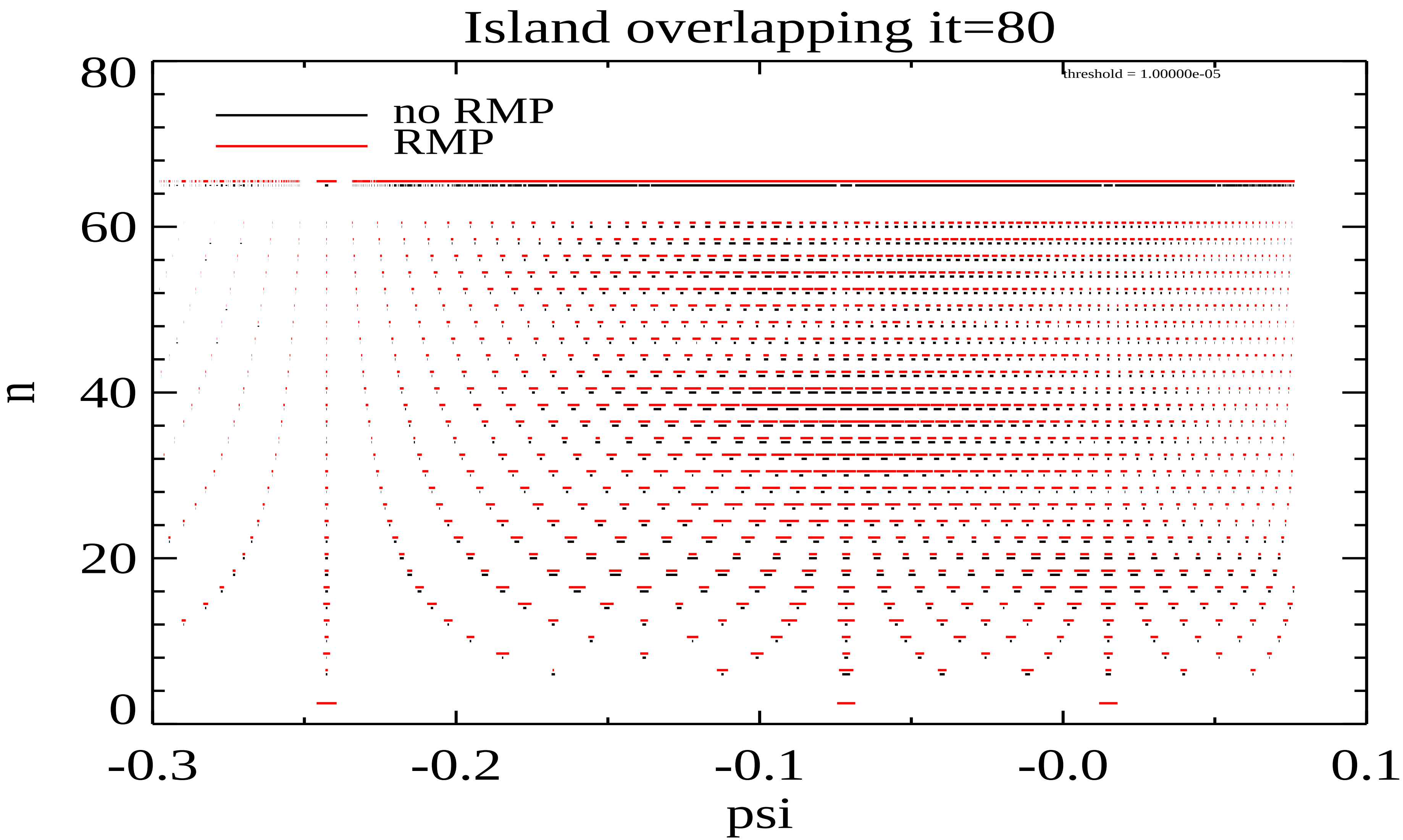
- With RMPs, one more cycle takes places. This time with $n = 10$ (PBM and PTM) and $n = 20$ (STM). $\Longrightarrow$ $n = 10$ tearing fluctuation feeds off $n = 20$ tearing fluctuation.
- Through the consecutive nonlinear generation of tearing parity fluctuation, the island width is determined by a lower toroidal number than in the absence of RMPs.



- This can happen because $n = 10$ ballooning parity fluctuation is enhanced in the presence of RMPs.

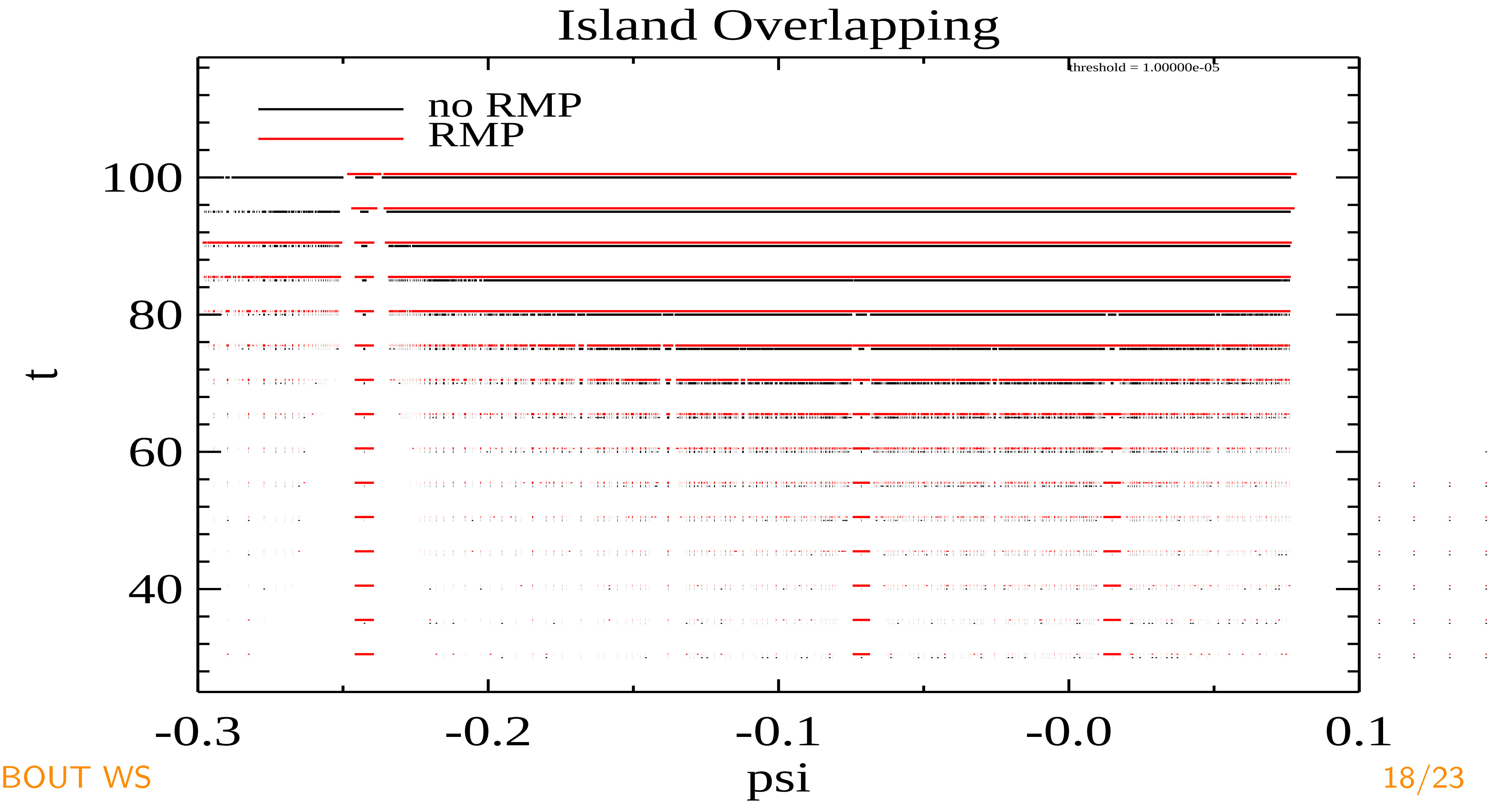
Larger tearing parity fluctuations in RMPs

- With RMPs, magnetic islands for all rational surfaces have larger widths.



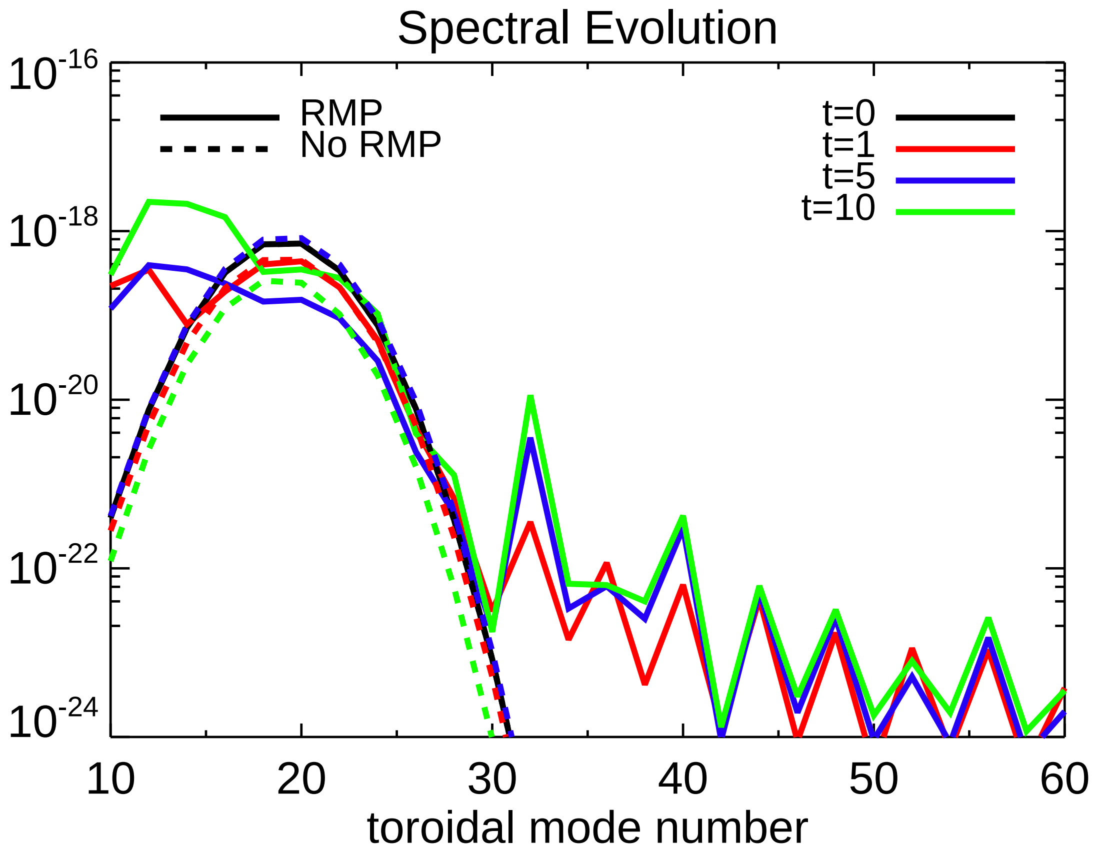
Low rational surfaces are the last to be destroyed

The rational surfaces of smaller m and n are the last to be overlapped, since the distance to the neighboring surfaces is the longest.



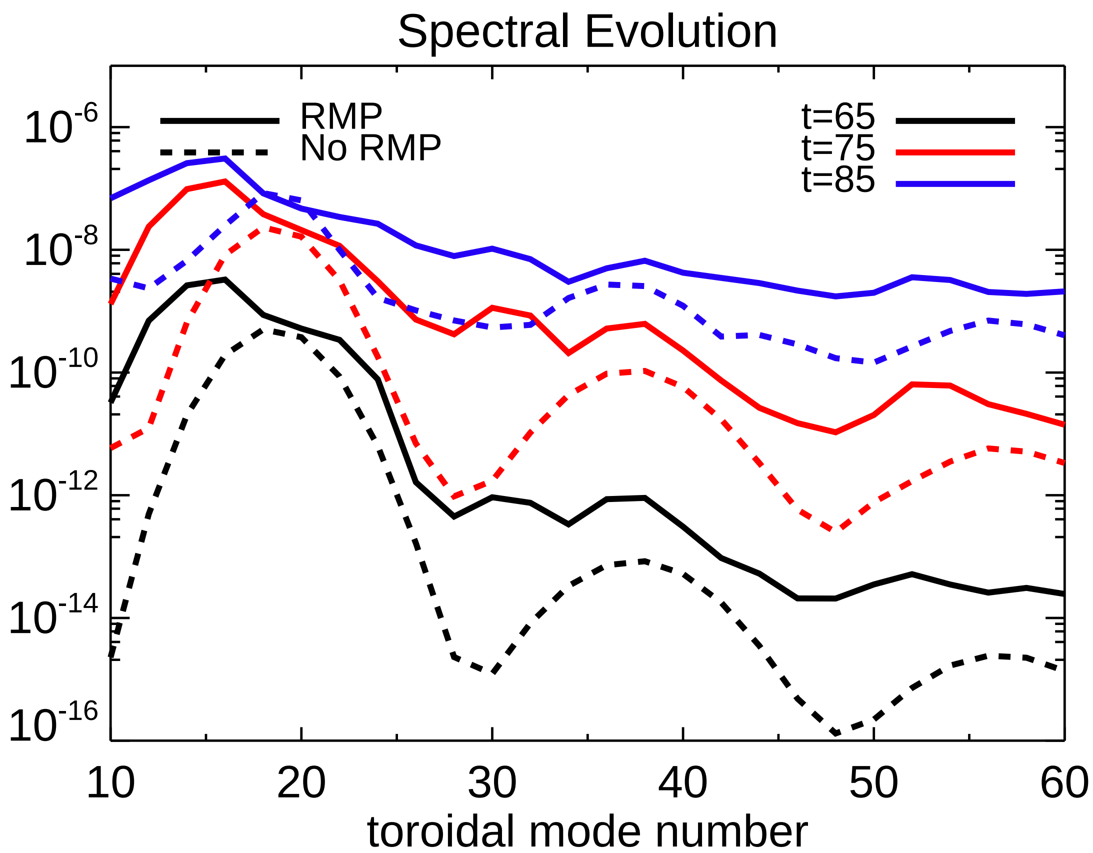
Enhanced and broader spectrum from the beginning

- Right after the start of the simulation, the broad spectrum is quickly established and stay for a few more Alfvén time, until the unstable modes find their eigenstructures.



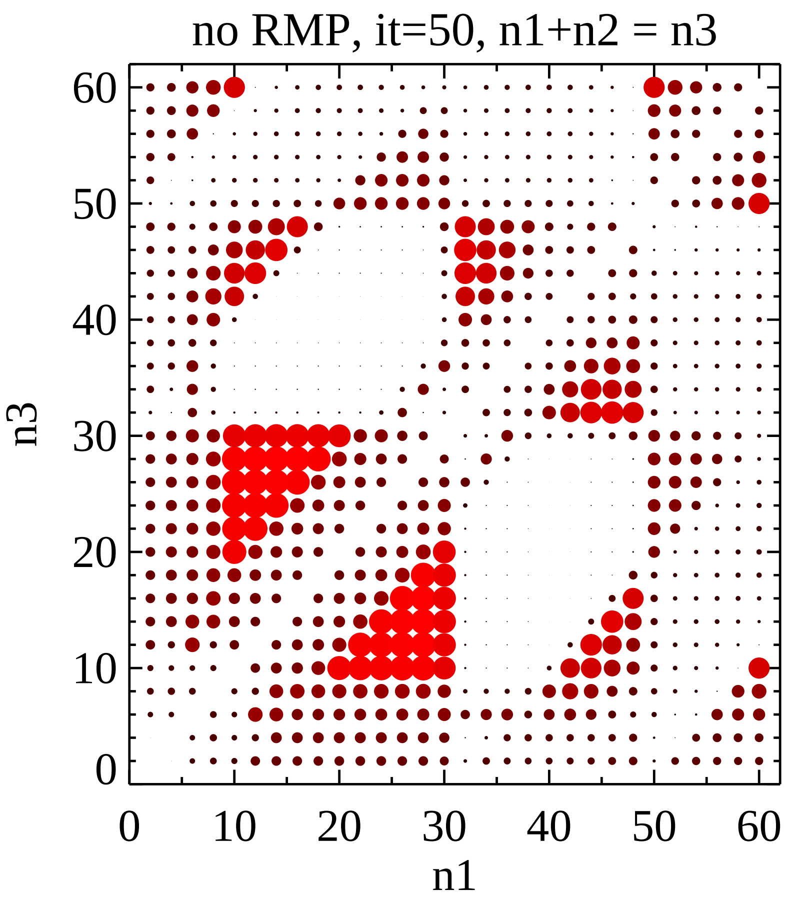
RMPs keep redistributing the energy

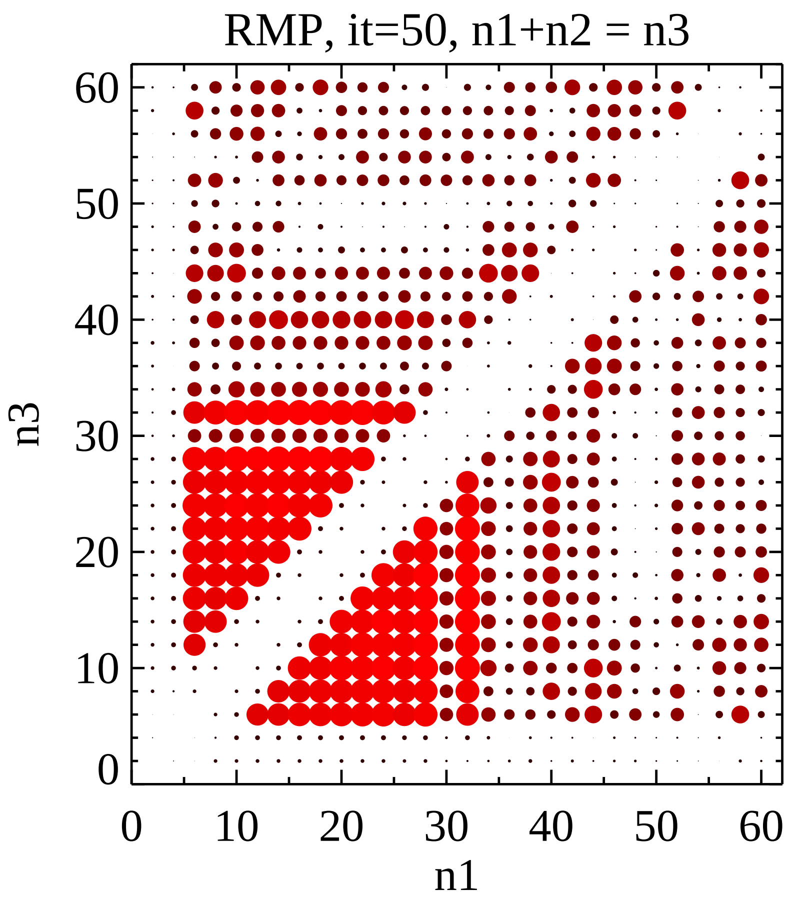
- As the fluctuations increase with instability, RMPs smoothen the spectrum in a way that they appear to transfer energy into higher and lower toroidal modes.
- Around $n = 20$, the fluctuation levels in the RMPs are similar to No RMPs. $\Longrightarrow$ That's where the linear growth rates are the largest.



With RMPs, more toroidal modes are nonlinearly correlated

- The bispectral analysis indicates that
  - In the pre-collapse phase, $n = 20 - 30$ modes are strongly correlated along with $n = 40 - 48 \implies$ Confirms the coherent interactions.
  - With RMPs, more toroidal mode numbers $n = 10 - 30$ are evenly correlated



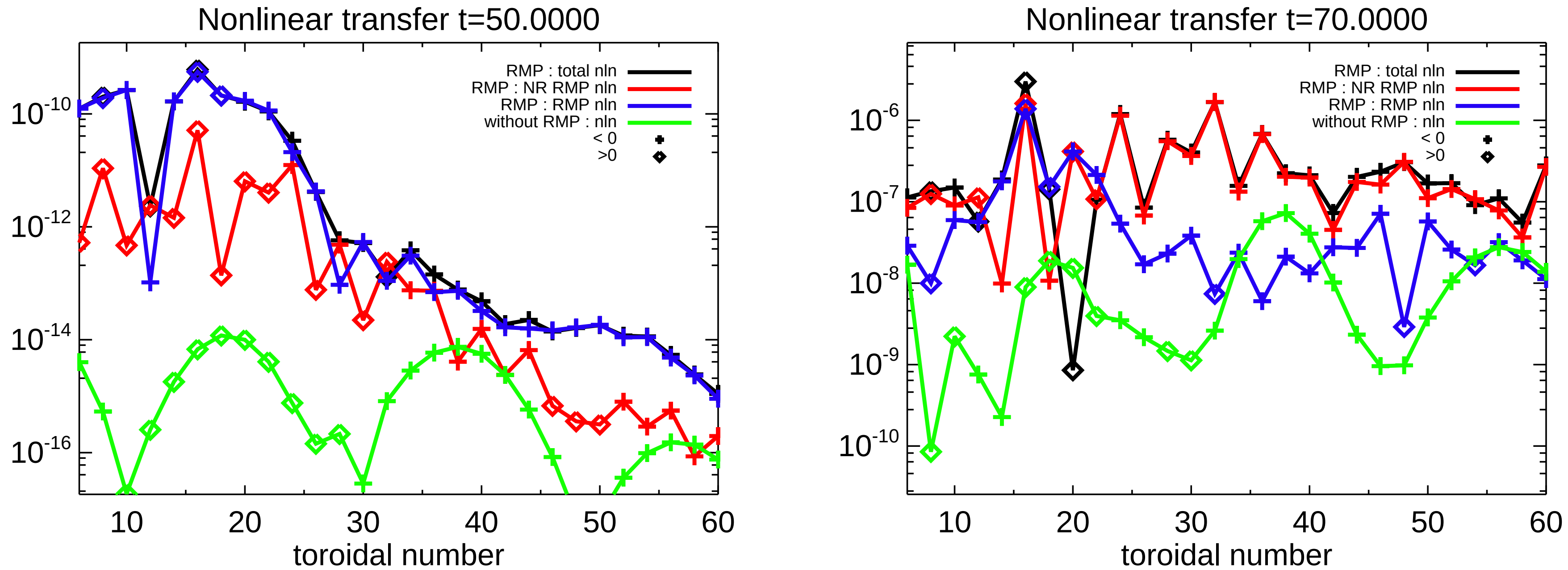


RMPs induce broad spectrum formation in the pre-collapse.

- Nonlinear energy transfer rate in Ohm's law is defined as

$$\Gamma(\psi) = \left\langle J_n \left[\psi^{\mathrm{tot}}, \phi\right]_n^* \right\rangle = \left\langle J_n \left[\tilde{\psi}, \phi\right]_n^* \right\rangle + \left\langle J_n \left[\psi^{\mathrm{RMP}}, \phi\right]_n^* \right\rangle$$

- Energy flow from a toroidal number n ($\Diamond$) to a toroidal number n' ($+$)



- RMPs mediate energy transfer from $n = 16 \sim 18$ to all other toroidal modes, confirming the RMPs keep redistributing energy and increase the fluctuation levels.
- Later close to the collapse, the role of RMP becomes less significant.

Conclusion

- We have studied the evolution of the ballooning driven fluctuations in the pedestal collapse simulations with/without RMPs.
- It is found that
  - Even in the multi-n simulations, the nonlinear generation of tearing parity fluctuations by ballooning parity fluctuations can explain stochastization, qualitatively.
  - The presence of RMPs can increase the fluctuation level, especially at low toroidal modes, and increases convective transport.
  - RMP mediated nonlinear coupling of toroidal modes is a key mechanism for broad and enhanced fluctuations.
- RMPs may play a similar role for turbulence responsible for pedestal transport.
- Future plans
  - Dependence on dominant toroidal mode numbers
  - Dependence on plasma responses (linear vs nonlinear, pitch vs. kink-dominant)

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